

Complementarity in a macroscopic observation

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Complementarity is usually considered as a phenomenon of microscopic systems. In this paper we report an experimental observation of complementarity in the correlated double-slit interference with a pseudothermal light source. The thermal light beam is divided into test and reference beams which are correlated with each other. The double-slit is set in the test arm, and the interference pattern can be observed in the intensity correlation between the two arms. The experimental results show that the disappearance of interference fringe depends on whether which-path information is gained through the reference arm. The experiment therefore witnesses the complementarity occurring in a macroscopic system.

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Since the principle of complementarity was originally proposed in the dialogue between Bohr and Einstein it has drawn much attention and aroused interesting debates in the past years[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The principle states that simultaneous observation of wave and particle behavior of a microscopic system is prohibited. In a Young's double-slit interference experiment, for example, one can never simultaneously obtain exact knowledge of the photon trajectory (particle behavior) and the interference fringes (wave behavior). To be precise, if the photon trajectory is definitely known, no interference pattern can be observed. Accordingly, if an interference pattern is recorded, the photon path cannot be distinguished.

As quantum phenomena occurring in the microscopic realm, the original gedanken experiments and the following experimental implementations of complementarity involved individual microscopic particles or photons[2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. In this paper we report the observation of complementarity between interference fringe and which-path knowledge in a correlated double-slit interference experiment with thermal light. We describe this as a *macroscopic observation* since the source used in our experiment is a pseudothermal light beam and measurement is performed by ordinary optical intensity detection, rather than single-photon detection. To avoid direct measurement, we utilize the spatial correlation of thermal light to set up a telltale apparatus and gain which-path information.

Recent studies have shown that a thermal light source can play a role similar to that of a two-photon entangled source in "ghost" imaging, "ghost" interference and subwavelength interference[17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. When a thermal light beam random in its transverse wavevector illuminates a double-slit, the interference pattern does not appear in the intensity distribution but can be extracted in the intensity correlation[22, 23, 24, 25]. On the other hand, the thermal light can also mimic entangled photon pairs in performing ghost imaging[17, 18, 19, 20, 21, 26]. By analyzing different correlation features between entangled photon pairs and thermal light, Ref. [19] first pointed out that thermal light can, moreover, exhibit ghost imaging without using any lenses. That is, the beamsplitter which divides the thermal light into two beams acts as a phase conjugate mirror and a conjugate image can be formed at the symmetric position of the object with respect to the beamsplitter. It thus establishes point-to-point correspondence between the object and image. As a result, ghost imaging manifests particle-like behavior: if one photon illuminates a point on the object, the other photon must arrive at the corresponding position of the image. The path information of photons in one arm can be extracted by knowledge of the other arm of the beamsplitter.

In this paper we discuss two experimental schemes. The first is depicted in Fig. 1. A pseudothermal light beam, which is formed by a He-Ne laser beam projected onto a rotating ground glass, is divided by two 50/50 beamsplitters (BS1 and BS2) into three beams: one test beam which illuminates a double-slit, and two reference beams which propagate freely. Three charge-coupled device (CCD) cameras are used to register the beam intensity in each arm: CCD1 detects the intensity of the beam passing through the double-slit in the test arm while CCD2 and CCD3 register the intensity distributions in the two reference arms. We place CCD2 at the symmetric position of the double-slit with respect to BS2 and CCD3 in the far field, thus, in the intensity correlation with CCD1, the former may show ghost imaging and the latter ghost interference. This scheme is similar to that proposed in Ref. [27] where the authors reported experimentally that ghost imaging and ghost interference can be implemented simultaneously with an entangled two-photon state, and claimed this would be a distinction between classically correlated and quantum entangled systems.

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Figure 2 shows the experimental results. Note that CCD2 and CCD3 register the intensity distributions $I_2(x_2)$ and $I_3(x_3)$ across the reference arms, respectively, while CCD1 detects the intensity $I_1(x_1)$ at a fixed position $x_1 = 0$ in the test arm. In Fig. 2a the normalized intensity correlation between CCD1 and CCD2 $\langle I_1(0)I_2(x_2) \rangle / (\langle I_1(0) \rangle \langle I_2(x_2) \rangle)$ shows a conjugate image of the double-slit, and in Fig. 2b, the correlation $\langle I_1(0)I_3(x_3) \rangle / (\langle I_1(0) \rangle \langle I_3(x_3) \rangle)$ between CCD1 and CCD3 exhibits an interference pattern. This demonstrates that ghost imaging and ghost interference can be simultaneously observed with a pseudothermal light source. Nevertheless, the experimental results do not display any complementarity between interference and imaging. In this experiment the photons which participate in ghost imaging and have been detected by CCD2 are never involved in the interference, and vice versa.

We now propose another scheme to monitor the which-path information in the correlated double-slit interference. As shown in Fig. 3, the double-slit is placed in the test arm, but now a single-slit is inserted into the reference arm at the position that is exactly symmetric relative to the beamsplitter and coincides with one slit of the double-slit in the test arm. This single-slit plays the telltale role as a measuring apparatus due to the point-to-point correspondence between object and image. That is, the which-path information of the double-slit interference in the test arm can be obtained through the single-slit in the reference arm.

To demonstrate the ghost interference, CCD1 and CCD2 register the intensity $I_1(x_1)$ after the double-slit and $I_2(x_2)$ after the single-slit, respectively. Figure 4a shows the normalized intensity correlation $\langle I_1(x_1)I_2(x_2) \rangle / (\langle I_1(x_1) \rangle \langle I_2(x_2) \rangle)$, where the left plot indicates the correlation distribution measured by scanning the position x_1 in the reference arm for a fixed position $x_2 = 0$ in the test arm, and vice versa for the right plot. The two correlation curves do not exhibit any interference patterns.

One might think that the disappearance of interference in the above scheme is due to the disturbance of an aperture inserted into the reference arm. In order to confirm the effectiveness of the present telltale apparatus, in Fig. 3, we next replace the single-slit in the reference arm with a double-slit, which is exactly the same as in the test arm. In this case the which-path information is completely erased. The correlation measurement results are shown in Fig. 4c, where we can see that the correlated interference fringes reappear with a higher visibility than in Fig. 2 of the first scheme. Furthermore, when we partly cover one slit of the double-slit in the reference arm, incomplete which-path information is gained. Figure 4b shows that although the interference fringes are still observed they have a lower visibility. These experimental results clearly demonstrate the complementarity in correlated double-slit interference with thermal light: any attempt to extract path information from the reference arm shall degrade the interference fringe visibility.

Our experimental results can be explained by considering the spatial correlation properties of thermal light. The thermal light source used in the experiment is described by the field distribution $E(\mathbf{x}, z, t) = \int \tilde{E}(\mathbf{q}) \exp[i\mathbf{q} \cdot \mathbf{x}] d\mathbf{q} \times \exp[i(kz - \omega t)]$, where z is the propagation direction and \mathbf{x} and \mathbf{q} the transverse position and wavevector, respectively. According to the Wiener-Khintchine theorem, the first-order spectral correlation of the stochastic field $\tilde{E}(\mathbf{q})$ can be written as $\langle \tilde{E}^*(\mathbf{q}) \tilde{E}(\mathbf{q}') \rangle = W(\mathbf{q}) \delta(\mathbf{q} - \mathbf{q}')$, where $W(\mathbf{q})$ is the power spectrum of the spatial frequency. By Fourier transform the first-order spatial correlation of the field is given by $\langle E^*(\mathbf{x}) E(\mathbf{x}') \rangle = \tilde{W}(\mathbf{x} - \mathbf{x}')$, where the correlation function $\tilde{W}(\mathbf{x}) = \frac{1}{2\pi} \int W(\mathbf{q}) \exp(i\mathbf{q} \cdot \mathbf{x}) d\mathbf{q}$. For thermal light, the second-order spatial correlation satisfies

$$\langle E^*(\mathbf{x}_1) E^*(\mathbf{x}_2) E(\mathbf{x}'_2) E(\mathbf{x}'_1) \rangle = \langle E^*(\mathbf{x}_1) E(\mathbf{x}'_1) \rangle \langle E^*(\mathbf{x}_2) E(\mathbf{x}'_2) \rangle + \langle E^*(\mathbf{x}_1) E(\mathbf{x}'_2) \rangle \langle E^*(\mathbf{x}_2) E(\mathbf{x}'_1) \rangle. \quad (1)$$

We now consider the propagation of the field in the test and reference arms. Let $E(\mathbf{x})$ be a source field, so the outgoing field is obtained as

$$E_j(\mathbf{x}) = \int h_j(\mathbf{x}, \mathbf{x}') E(\mathbf{x}') d\mathbf{x}', \quad (j = 1, 2) \quad (2)$$

where $h_j(\mathbf{x}, \mathbf{x}_0)$ ($j = 1, 2$) is the transfer function describing the test and reference systems, designated by indices 1 and 2, respectively. The intensity correlation between the test and reference arms can be calculated from

$$\begin{aligned} \langle I_1(\mathbf{x}_1) I_2(\mathbf{x}_2) \rangle &= \langle E_1^*(\mathbf{x}_1) E_2^*(\mathbf{x}_2) E_2(\mathbf{x}_2) E_1(\mathbf{x}_1) \rangle \\ &= \langle I_1(\mathbf{x}_1) \rangle \langle I_2(\mathbf{x}_2) \rangle + |\langle E_1^*(\mathbf{x}_1) E_2(\mathbf{x}_2) \rangle|^2, \end{aligned} \quad (3)$$

where

$$\langle I_j(\mathbf{x}) \rangle = \frac{1}{2\pi} \int h_j^*(\mathbf{x}, \mathbf{x}'_0) h_j(\mathbf{x}, \mathbf{x}_0) \tilde{W}(\mathbf{x}'_0 - \mathbf{x}_0) d\mathbf{x}'_0 d\mathbf{x}_0, \quad (j = 1, 2) \quad (4a)$$

$$\langle E_1^*(\mathbf{x}_1) E_2(\mathbf{x}_2) \rangle = \frac{1}{2\pi} \int h_1^*(\mathbf{x}_1, \mathbf{x}'_0) h_2(\mathbf{x}_2, \mathbf{x}_0) \tilde{W}(\mathbf{x}'_0 - \mathbf{x}_0) d\mathbf{x}'_0 d\mathbf{x}_0. \quad (4b)$$

In Eq. (3) the first term contributes a background, and the second term may contain the coherence information, which can be extracted by intensity correlation measurements.

For simplicity we consider the one-dimensional case. The transfer function for free travel over a distance z is given by

$$h(x, x_0) = \sqrt{\frac{k}{2\pi iz}} \exp(ikz) \exp\left[ik \frac{(x - x_0)^2}{2z}\right]. \quad (5)$$

Thus the field correlation between the test and reference arms at the same distance z is obtained as

$$\begin{aligned} \langle E_1^*(x_1) E_2(x_2) \rangle &= \frac{k}{(2\pi)^{3/2} z} \exp\left[i \frac{k}{2z} (x_2^2 - x_1^2)\right] \\ &\times \int \exp\left[i \frac{k}{2z} (x_0^2 - x_0'^2 - 2x_0 x_2 + 2x_0' x_1)\right] \widetilde{W}(x_0' - x_0) dx_0 dx_0'. \end{aligned} \quad (6)$$

In the broadband limit of the spectrum, $\widetilde{W}(x) \rightarrow \sqrt{2\pi} W_0 \delta(x)$, Eq. (6) becomes

$$\langle E_1^*(x_1) E_2(x_2) \rangle = W_0 \delta(x_1 - x_2) \quad (7)$$

which shows a point-to-point correspondence of the field amplitudes between the two arms. This feature is also reflected in the intensity correlation of Eq. (3). In the quantum regime, however, Eq. (3) describes a two-photon coincidence probability. Therefore, knowledge of a photon's position in one arm implies knowledge of the position of the correlated photon in the other arm. This provides telltale information about the photon paths without disturbing the interference system. Moreover, Eqs. (6) and (7) are the origin of correlated imaging without the use of lenses.

When an object of transmission $T(x)$ is inserted in the test arm, the transfer function is written as

$$h(x, x_0) = \frac{k}{i\sqrt{2\pi z_0 z}} \exp[ik(z_0 + z)] \exp\left[i \frac{k}{2} \left(\frac{x^2}{z} + \frac{x_0^2}{z_0}\right)\right] \widetilde{T}\left[k \left(\frac{x}{z} + \frac{x_0}{z_0}\right)\right], \quad (8)$$

where \widetilde{T} is the Fourier transform of T ; z_0 and z are the distances from source to object and from object to detector, respectively. In the paraxial approximation, for a double-slit $D(x)$ and a single-slit $S(x)$, $\widetilde{T}(q)$ is replaced by

$$\widetilde{D}(q) = (2b/\sqrt{2\pi}) \text{sinc}(qb/2) \cos(qd/2), \quad (9a)$$

$$\widetilde{S}(q) = (b/\sqrt{2\pi}) \text{sinc}(qb/2) \exp(-iqd/2), \quad (9b)$$

respectively, where b is the slit width and d is the distance between the centers of two slits.

In the broadband limit, by using Eqs. (4), (8) and (9) we obtain the analytical solution of the intensity correlation for the scheme of Fig. 3. When a double-slit and a single-slit are inserted into the reference arm, we obtain

$$\langle I_1(x_1) I_2(x_2) \rangle = \frac{k^2 W_0^2}{2\pi z^2} \left\{ \widetilde{D}^2(0) + \widetilde{D}^2\left[\frac{k}{z}(x_1 - x_2)\right] \right\}, \quad (10a)$$

$$\langle I_1(x_1) I_2(x_2) \rangle = \frac{k^2 W_0^2}{2\pi z^2} \left\{ \widetilde{D}(0) \widetilde{S}(0) + \left| \widetilde{S}\left[\frac{k}{z}(x_1 - x_2)\right] \right|^2 \right\}, \quad (10b)$$

respectively, where z is the distance between the slit and detector. Equation (10a) gives interference fringes with a visibility of 33.3%, which is the maximum obtainable in correlated double-slit interference (see Fig. 4c). Instead of interference fringes, however, Eq. (10b) produces a diffraction pattern, as seen in Fig. 4a.

As for the incomplete double-slit in the reference arm where the width of one slit is reduced to one quarter, its Fourier function is given by

$$\widetilde{Q}(q) = \widetilde{S}(q) + \frac{b}{4\sqrt{2\pi}} \text{sinc}\left(\frac{qb}{8}\right) \exp[iq(\frac{d}{2} - \frac{3b}{8})]. \quad (11)$$

The correlation function is calculated to be

$$\langle I_1(x_1) I_2(x_2) \rangle = \frac{k^2 W_0^2}{2\pi z^2} \left\{ \widetilde{D}(0) \widetilde{Q}(0) + \left| \widetilde{Q}\left[\frac{k}{z}(x_1 - x_2)\right] \right|^2 \right\}, \quad (12)$$

and the interference fringes have a visibility of 23.8% (see Fig. 4b) lower than that for the complete double-slit. The numerical simulations agree well with the experimental data.

In summary, the correlated double-slit interference phenomenon of thermal light manifests wave behavior. However, the correlated imaging of thermal light exhibits particle-like behavior since it indicates the position-position correspondence between two beams. We have demonstrated that, in the correlated double-slit interference, any attempt to acquire path-information from the reference system will destroy the interference. The present experiment can be considered as a macroscopic observation of the complementarity, and may promote our knowledge of the quantum world.

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Figure captions:

Figure 1. Schematic of experimental setup for simultaneously observing ghost imaging and ghost interference with a pseudo-thermal light beam. The source beam is split into three by two beamsplitters (BS1 and BS2), and their intensities can be adjusted by polarizers P_1 , P_2 , and P_3 , and then registered by three charge coupled device (CCD) cameras (MINTRON:MTV-1881EX). The double-slit has a slit width $b = 85\mu m$ and slit-center separation $d = 330\mu m$. The distances from the ground glass to the double-slit, CCD1, CCD2, and CCD3 are 10, 30, 10, and 44cm, respectively.

Figure 2. Experimental data of intensity distributions (solid squares) and normalized intensity correlations (circles) registered by (a) CCD2 and (b) CCD3. In the measurements, CCD1 detects a fixed position in the test arm while CCD2 and CCD3 register the intensity distributions across the reference arms. Numerical simulations are shown by solid lines.

Figure 3. Schematic of experimental setup for observing the complementarity with pseudo-thermal light. The reflected (test) arm contains a double-slit, while the transmitted (reference) arm may contain a single-slit, a double-slit, or an incomplete-slit. The distances from the ground glass to the double-slit, the reference arm slits, CCD1, and CCD2 are 2, 2, 42 and 42cm, respectively.

Figure 4. Experimental data of intensity distributions (solid squares) and normalized intensity correlations (circles) for (a) a single-slit, (b) an incomplete double-slit, and (c) a double-slit placed in the reference arm. The left column figures show the results when CCD1 detects a fixed position in the test arm while CCD2 registers the intensity distribution across the reference arm, and vice versa for the right column. Numerical simulations are shown by solid

lines.







